

Sea Spray: Its Production, Near-Surface Distribution, and Effect on Surface Heat and Moisture Fluxes

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LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat and moisture across the air-sea interface, especially in high winds. Ultimately, we hope to develop simple parameterizations for these air-sea fluxes for use in large-scale models.

OBJECTIVES

The biggest impediment to progress in this area is poor knowledge of the rate at which sea spray droplets of various sizes are produced at the air-sea interface. Thus, the first objective is to better quantify the sea spray generation function. Two classes of spray droplets exist: those derived from bursting bubbles (either film or jet droplets) and those torn directly from wave crests by the wind (spume droplets). The spray generation function for each class likely depends on wind speed, water temperature, sea state, and surface contaminants. The second objective is to develop parameterizations, based on microphysical modeling, for the rate at which individual spray droplets exchange heat and moisture with their environment. The third objective is then to couple the spray generation function with the microphysical modeling to estimate the integrated contribution of all spray droplets to the surface heat and moisture fluxes. A related objective is to quantify how the feedback between the elevated spray heat and moisture sources alters the interfacial transfer (the turbulent air-sea transfer that obtains in the absence of spray).

APPROACH

This work is theoretical and analytical; there has been no experimental component. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theoretical considerations also predict how the sea spray generation function should depend on wind speed. The analytical part involves developing parameterizations for the various processes under consideration by simplifying model results or by synthesizing various data sets and observations reported in the literature. Checking the parameterizations being developed against available data is also another aspect of what I call analytical work.

A lot of work has been done on the physics of air-sea interaction and the details of the atmospheric surface layer above the sea surface. Although laboratory studies (e.g., Mestayer and Lefauconnier,

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 1998		2. REPORT TYPE		3. DATES COVERED 00-00-1998 to 00-00-1998	
4. TITLE AND SUBTITLE Sea Spray: Its Production, Near-Surface Distribution, and Effect on Surface Heat and Moisture Fluxes				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH, 03755				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002252.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 5	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

1988), numerical spray droplet models (e.g., Rouault et al., 1991; Edson et al., 1996), and open-ocean observations (e.g., Korolev et al., 1990) all show that sea spray can redistribute heat between the temperature and humidity fields in the marine boundary layer (MBL), no work has shown conclusively that sea spray can enhance the net air-sea heat exchange. The net air-sea heat flux, rather than the redistribution of MBL heat, is what is important in predicting the intensity of tropical cyclones (Andreas and Emanuel, 1999). Few measurements have been made in winds above 20 m/s, however, where my modeling suggests that spray finally becomes a significant transfer mechanism. Consequently, another aspect of my approach is to make certain that predictions from my spray model are compatible with previous observations of air-sea heat and moisture fluxes.

WORK COMPLETED

The spray generation function that I developed (Andreas, 1992) has yielded useful results (e.g., Fairall et al., 1994; Andreas and DeCosmo, 1998) but is limited to wind speeds of 20 m/s or less. I have, thus, developed a new spray generation function, based on the model reported in M. H. Smith et al. (1993), that treats winds up to 32 m/s. That is, this new model can predict spray generation in winds of almost hurricane strength, where the hurricane community (e.g., Emanuel, 1986, 1997; R. K. Smith, 1997) has long been invoking an unidentified source of latent heat to maintain hurricanes. The paper describing that model is scheduled to be published in *Journal of Physical Oceanography* before the end of the year (Andreas, 1998).

The original Andreas (1992) spray generation function and this new one (Andreas, 1998) figure prominently in a review paper on sea spray that I co-authored with Janice DeCosmo (Andreas and DeCosmo, 1998). That manuscript reviews sea spray generation processes and focuses on the two Andreas (1992, 1998) models as having the best theoretical behavior. On the basis of these two models, we develop a simple estimate for the distribution of droplets in the so-called droplet evaporation layer (Andreas et al., 1995). On vertically integrating this distribution, we estimate how sea spray effectively increases the surface area of the ocean. For a 10-meter wind speed of 20 m/s, the two spray generation models predict that the fractional surface area of the spray above a unit area of sea surfaces is 5-10%. But spray generation increases roughly as the third power of the wind speed; thus, for a wind of 32 m/s, the Andreas (1998) function predicts that the surface area of the spray above a square meter of ocean is 0.7 m^2 . In other words, the surface area of the spray is 70% of the ocean's surface area. It is hard to discount such a huge effect: In high winds, sea spray must play a significant role in air-sea heat and moisture transfer.

Because the net air-sea enthalpy flux is what affects hurricane generation and maintenance, Emanuel (1995) concludes that spray cannot be important to the thermodynamics of tropical cyclones: The MBL must provide the heat to evaporate the spray droplets; thus, he sees no net air-sea heat flux. I have since convinced him otherwise (Andreas and Emanuel, 1999); but during our discussions, he (K. A. Emanuel, 1997, personal communication) suggested that air heated and moistened in whitecap bubbles could also accomplish a net air-sea enthalpy transfer. As a result of this discussion, Ed Monahan and I evaluated the potential air-sea sensible and latent heat fluxes that bubbles would foster and found both negligible for wind speeds up to 40 m/s (Andreas and Monahan, 1998). This conclusion leaves us still with sea spray as the most likely source of the anomalous heat necessary to generate and maintain tropical cyclones.

In fact, this year we finally succeeded in quantifying this anomalous spray flux. Using the HEXOS (Humidity Exchange over the Sea Experiment) eddy-correlation measurements of sensible and latent heat flux (DeCosmo et al., 1996), the Andreas (1992) spray model, and both of the Andreas (1992, 1998) spray generation functions, Andreas and DeCosmo (1998) could identify a spray signal in the measured HEXOS heat fluxes. That is, besides redistributing the heat in the MBL, the spray also accomplishes a net air-sea enthalpy flux that is roughly 10% of the interfacial enthalpy flux for wind speeds up to 20 m/s (Andreas and Emanuel, 1999). This enthalpy flux is largely carried by the spray droplets as sensible heat; Emanuel (1995) had overlooked this route when he concluded that spray could not affect hurricane dynamics. In summary, we have quantified spray's role as, at least, a partial source of the anomalous heat necessary for generating and maintaining tropical cyclones.

RESULTS

As a result of work this year, I have developed two models that predict the air-sea fluxes of sensible and latent heat—including the effects of sea spray. One, based on the Andreas (1992) spray generation function, is good for wind speeds up to 20 m/s; the second, based on the Andreas (1998) spray generation function, is good for winds up to 32 m/s—the lower limit for hurricanes. In contrast, the best current parameterization for the air-sea heat fluxes—the TOGA-COARE algorithm (Fairall et al., 1996)—is untested for winds as high as 20 m/s and contains no explicit spray parameterization.

As I mentioned above, these two models, when combined with the HEXOS flux measurements, lead to the prediction that spray can account for at least 10% of the net air-sea enthalpy flux for winds up to 20 m/s (Andreas and Emanuel, 1999). Since spray production goes as the third power of the wind speed, we infer that spray can truly enhance the net enthalpy flux in winds of hurricane strength and, thus, must provide at least part of the missing heat flux that the hurricane community has been seeking.

As a slight but necessary digression from my main focus on sea spray, this year I evaluated the role that air cycled through whitecap bubbles plays in air-sea heat and moisture exchange (Andreas and Monahan, 1998). Simply because the air in whitecap bubbles has so little mass and so little volume, we found that bubbles produce negligible heat transfer for winds up to 40 m/s.

IMPACT

In finding that sea spray can accomplish a net enthalpy exchange across the air-sea interface, we have identified an unappreciated source of energy that can influence the intensity of tropical storms. Fairall et al (1994) were the first to investigate how sea spray could affect the development of the MBL in a tropical cyclone and confirmed that the spray does redistribute heat between the temperature and humidity fields. In light of my work this year, Kerry Emanuel (Andreas and Emanuel, 1999) incorporated some rudimentary spray processes in his tropical cyclone model (Emanuel, 1995) and thereby illustrated dramatic effects of sea spray on maximum cyclone wind speed. That is, not only does the spray redistribute heat in the atmosphere, it can actually transfer energy across the air-sea interface and therefore affect storm intensity.

We will continue trying to improve predictions of hurricane intensity by refining the parameterizations for spray effects in large-scale cyclone models.

RELATED PROJECTS

There are no other funded spray projects at CRREL. I have, however, managed to modestly leverage my ONR funding with my base CRREL funding. This, for example, provides overhead support for secretaries, computer specialists, library staff, publications charges, and for miscellaneous supplies. In the past year, I have also leveraged my ONR funds by collaborating on this spray research with Janice DeCosmo at the University of Washington, Ed Monahan at the University of Connecticut, and Kerry Emanuel at MIT, who are funded under projects at their own institutions.

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IN-HOUSE/OUT-OF-HOUSE RATIOS

All of the work funded under this project was performed at CRREL, an Army Corps of Engineers Laboratory.